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# WIND TUNNEL EVALUATION FOR CONTROL TRANSITION FROM ELEVATOR TO STABILATOR OF SMALL UAV

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**Abstract**

Faulty control surface actuator in a small Unmanned Aerial Vehicles (sUAV) could be overcome with a few techniques. Redundant actuators, analytical redundancy or combination of both are normally used as fault accommodation techniques. In this paper, the accommodation technique of faulty elevator actuator is presented. This technique uses a standby control surface as temporary control reallocation. Wind tunnel measurement facility is set up for the experimental validation and it is compared with FoilSim software. Flat plate airfoil which was used as horizontal stabilizer, is simulated using numerical model and it is validated using the wind tunnel test. Then, a flat airfoil is designed to be used as stabilator for the recovery of faulty elevator actuator. Results show the different deflection angle is needed when transferring from one control surface to another. From the analysis, the proposed method could be implemented without affecting the pitch stability during control surface transition. The alternate control surface accommodation technique proves to be promising for higher reliability sUAV in the case of a faulty on-board actuator.

Keywords: UAV, Fault detection, Fault accommodation, FDI, Elevator fault.

## 1. Introduction

UAVs from micro to large scale are the common research topics in recent years. Small size UAVs are those having less than 3 meter wingspan and weight between 1-15 kg. The autopilot which was equipped in small UAVs usually do not have redundancy implemented and it is not prepared for emergency situations. To prevent serious damage to the UAV during an emergency, additional systems such as redundant hardware or redundant flight controller software is introduced.

In daily UAV operations, the UAV servo actuator, which controls the movement of the control surface, is exposed to the harsh environmental condition and mechanical stress. Most probable failure of UAV component comes from malfunction of servo actuator. Among the servo actuators installed, elevator servo actuator is the most crucial compared to aileron and rudder [1] since it provides increase or decrease of the lift force to control the aircraft [2] altitude. Figure 1 shows one of many cases where the gear within the servo actuator fails.


**Fig. 1. Faulty servo actuator.**

To prevent serious damage to the UAV, the fault accommodation techniques were explored by few researchers. Some of these techniques are analytical redundancy, data fusion and dual actuators [3].

Normally, in small UAV, either elevator or stabilator is actively used for longitudinal control of the vehicle. Figure 2(a) shows the use of all-moving horizontal stabilizer as longitudinal control. This technique is used, for example, by the PUMA UAV manufactured by Aeroviroment. The use of all-moving horizontal stabilizer is also employed by many fighter aircrafts to provide a better maneuverability. This is due to the bigger surface area of the horizontal stabilizer. The challenge in implementing the stabilator as a longitudinal control is the higher forces needed to move the control surface. Very precise control is also needed as it is very sensitive.

Figure 2(b) shows the use of elevator for longitudinal control. This is a common method that can be found on many UAVs to control the altitude. This method is widely used as it requires less powerful actuator and a smaller actuator, thus reducing the weight. The drawback of using elevator is less maneuverability of the aircraft compared to using stabilator.

To increase the reliability and availability of the UAV, one of the efforts is to design UAV which is capable of tolerating potential faults and prevent faults from developing into serious failure while providing a desirable performance [4-5]. Manned aircraft manufacturers provide high level of hardware redundancies [6] to improve the reliability, but the same redundancies used in small UAV might result in unacceptable increase in system weight and cost [7-8].

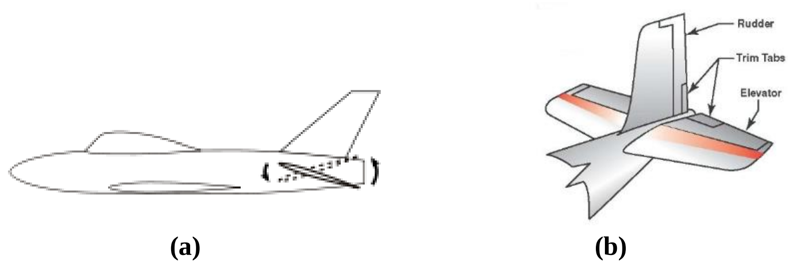


**Fig. 2. Aircraft longitudinal control (a) stabilator, (b) elevator.**

Automatically detecting the fault, finding the location and severity of it are crucial for unmanned vehicles. A simple and effective method implemented on-board must be robust and can be implemented in real-time applications [9]. When fault has been detected, control reallocation technique can then be applied to redistribute control effort amongst the available healthy actuators [10-11]. In this paper, a method to experimentally validate the concept to accommodate actuator fault in small Unmanned Aerial Vehicles is presented.

## 2. Background of Accommodation Technique

The proposed method of fault accommodation is by using redundancy in the control surface. The basis for this method is, once the actuator fault is detected, an alternate control method is used. In normal operation, an elevator is used primarily as the longitudinal control. Once the faulty actuator is detected, stabilator control is used temporarily to bring back the UAV safely. This method is explored due to its simple mechanism and low impact on the UAV weight. Furthermore, the actuator for the stabilator is in standby mode during normal operation and only activated if any fault occurs. Control reallocation has been reused recently due to the development of high performance and highly redundant aircraft [10].

There are also some researches on actuator redundancy by using dual actuators. This method has been explored by a research team in University of Minnesota [11]. The dual actuators are applied to the rudder of the UAV to control the yaw movement. While this method would provide emergency recovery if faulty actuator occurs, it is also faced with the probability of both the actuators fail at the same time. This is because the actuators are subjected to similar stress and workload.

Figure 3 shows the horizontal tail with control surface redundancy has been implemented. The white section is the elevator control surface which is used during normal operation. The blue section is the horizontal stabilizer surface which acts as stabilator when faulty elevator actuator occurred. A microcontroller is used for the fault detection and control surface reallocation process.

The transition from the elevator to stabilator needs to be smooth during the control reallocation. Without it, the UAV will be unstable thus leading to crash when the control reallocation commenced. The experimental setup section describes the hardware development and simulation to identify the flight characteristic during the transitional period.

**Fig. 3. All-moving horizontal stabilizer with trailing edge elevator.**

## 3. Experimental Setup

The experimental setup was divided into 2 categories. The first category was the development of the wind tunnel measurement. The second category was the experimental test of the flat airfoil to be used in the actual UAV.

To facilitate data collection, the data acquisition system for wind tunnel was developed. The development of data acquisition system is explained in 3.1. Next, the wind tunnel measurement system was validated using FoilSim, an airfoil simulation software. Finally, by using flat airfoil, the elevator actuator fault accommodation was designed and validated.

### 3.1. Wind tunnel measurement

Prior to implementing the accommodation technique to an actual flight, wind tunnel test was performed. The wind tunnel tests were conducted using low-speed open circuit wind tunnel. The wind tunnel test area dimension is 350 mm width by 350 mm length with 300 mm deep. The model blockage percentage is 1.4% which is better than recommended 7.5% [12]**.** The test provided numerical analysis data for the deflection angle needed during the transition from the elevator to stabilator. The results from the wind tunnel test were also used to validate the numerical model for the lift coefficient, *Cl*, of flat plate airfoil. Drag and lift force measurement have been made by using a load cell sensors. Figure 4 shows the configuration of the sensor to measure the lift and drag of the airfoil. Vertically oriented sensors were used to measure the lift while the horizontally aligned sensor was used to measure drag.

Suspended weight was used for calibration of the sensors. The linear equation of the lift and drag was computed and it was used for data measurement. After completing the sensor calibration process, NACA 2412 airfoil was used for the validation of the wind tunnel measurement. From the NACA 2412 airfoil wind tunnel experiment data, it was found that the error for the wind tunnel measurement was within 5% from the published data [12]. Furthermore, the experimental result shows the consistency of the *Cl, Cd* with data from [13].

Therefore, the wing tunnel data would provide reliable data to evaluate the performance of an airfoil.

**Fig. 4. Wind tunnel measurement setup.**

## 3.2. Flat airfoil validation

The chord of the flat airfoil test specimen used for the wind tunnel validation was 100 mm and the span was 300 mm with a thickness of 6mm. This particular airfoil was selected since it will be used in the UAV as the horizontal stabilizer. The horizontal stabilizer is shown in Fig. 5 was tested in the wind tunnel for experimental validation of the lift and drag data.

**Fig. 5. Test piece inside wind tunnel.**

Data from the wind tunnel test was used to validate the characteristic of the flat airfoil. The relationship between lift generated and the lift coefficient, $C_l$, is shown in Eq. (1).

$$L = C_l \times \frac{\rho V^2}{2} \times A \tag{1}$$

where L is lift, $C_l$ is lift coefficient, $\rho$ is air density in kg/m$^3$, $V$ is the air velocity in m/s and $A$ is wing area in m$^2$. $C_l$ is usually determined experimentally in wind tunnel test. Analytically, $C_l$ for flat plate airfoil, (if only small angles of attack are considered so that no flow separation occurs) can be determined [14] from Eq. (2).

$$C_l = 2\pi \propto \tag{2}$$

where $\propto$ is the angle expressed in radians.

## 4. Results and Discussion

### 4.1. Airfoil simulation

A software to analyze the lift coefficient called FoilSim was used in this study. FoilSim is a computer simulator program developed by NASA Glenn Research Center that calculates the total lift of a specified wing. Flat plate with a dimension of 300 mm × 100 mm (similar to wind tunnel test specimen) was used as the airfoil. The simulation was conducted using Reynolds number, Re, of 73000. This value of Reynolds number was used since the UAV will be operating around this condition. FoilSim simulation result indicated that the test specimen maximum lift occurred at angle of attack of 15.5° with lift coefficient of 1.237 as shown in Fig. 6. After 16° angle, the flat plate airfoil started to stall. Stall occurred when increasing the angle did not generate additional lift.

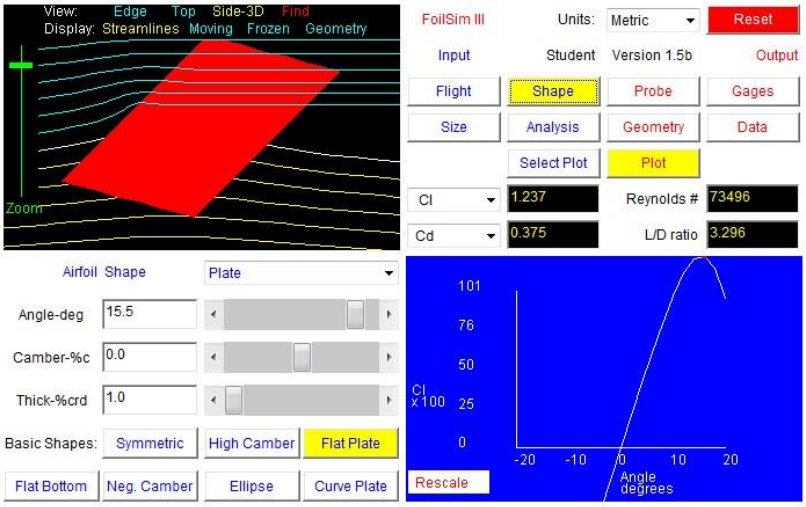


**Fig. 6. Foilsim analysis of flat plate airfoil.**

FoilSim results were compared with results from equation 2. Figure 7 shows the comparison results.

The numerical model shows a slightly higher lift coefficient compared to the FoilSim simulation. Since the numerical model only valid for a small angle, after 14° deflection onwards, the numerical estimation did not show any stall characteristics. On the other hand, FoilSim shows that the stall started to occur at 15°.

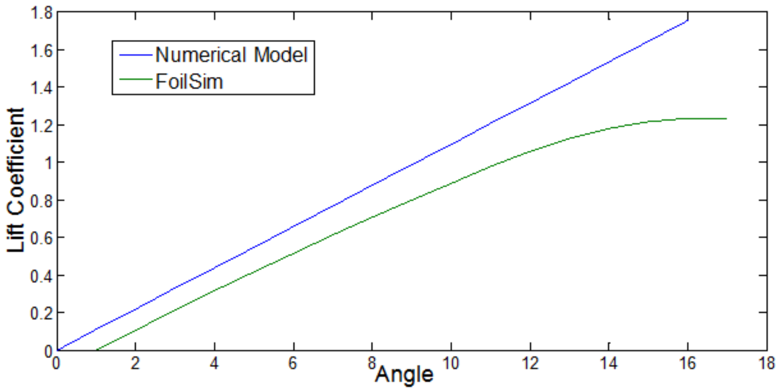


**Fig. 7. Estimation of lift coefficient using flat plate airfoil.**

## 4.2. Wind tunnel

Wind tunnel test was conducted to validate the simulation results. The tests were conducted with the flat airfoil positioned at 0° to 16° angle with 1° increment. The maximum angle of 16° was chosen as the maximum deflection based on the simulation result which predicts the stall occurs at 15 degree. Tests were conducted at a wind speed of 10 m/s.

By comparing the simulated and experimental results, the flat airfoil showed an early stall which occurs at 10° angle compared with the simulation which showed stall at 15°. The Wind tunnel test also indicated a slightly higher lift coefficient compared to numerical model and FoilSim simulation data. Maximum lift coefficient was also higher from wind tunnel test which was 1.7 compared with the lift coefficient from FoilSim simulation which was maximum at 1.2. With this data, the stabilator movement will be designed with movement less than 10° to prevent stall of the tail section. Comparison data from the wind tunnel test with simulation result is presented in Fig. 8.

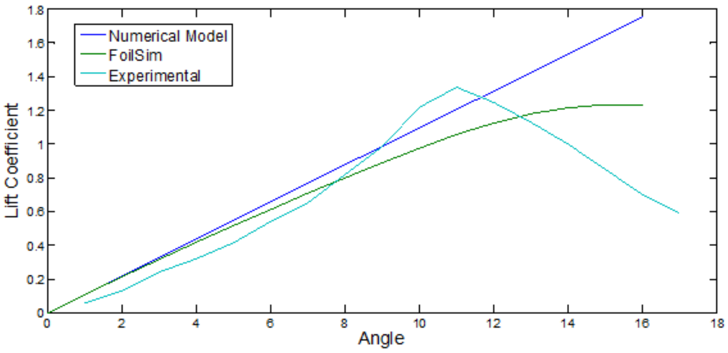


**Fig. 8. Test piece inside wind tunnel at speed of 10 m/s.**

Another test was conducted using the wind tunnel to compare the lift coefficient while using different elevator angle. An elevator control surface was embedded to the trailing edge of the flat airfoil. The elevator ratio was set at 30%

(which is 30 mm) of the chord length of the horizontal stabilizer while the span was similar to the horizontal stabilizer length which was 300 mm. Figure 9 shows the result from the test.

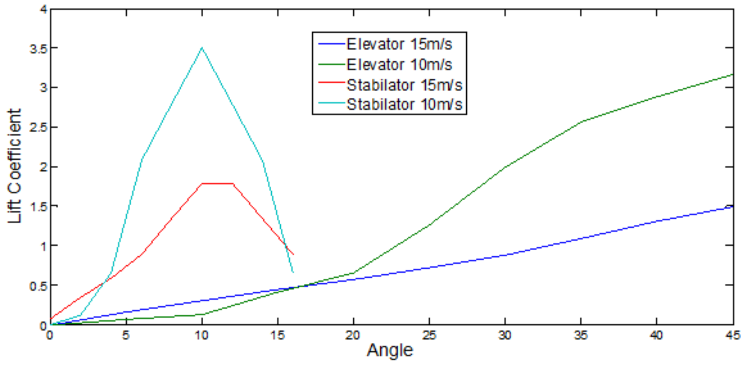


**Fig. 9. Lift coefficient using 2 different wind speeds.**

Wind speed of 10 m/s and 15 m/s were used for the tests. The tests were conducted using the elevator angle set at 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40° and 45° while maintaining the horizontal stabilizer at 0° angle relative to the wind.

Figure 10 shows the data from the test. The movement of the elevator can be as maximum as 45° without causing the airfoil to stall. On the other hand, the horizontal stabilizer started to stall at 11° angle. For the same lift coefficient, smaller deflection angle was also observed for the stabilator surface. For example, at a lift coefficient of 1.0, the elevator needs to be deflected at 24°, while the horizontal stabilizer needs only 4° of deflection at a wind speed of 15 m/s. In practical application, the movement of the elevator is limited to +-25°which translates to about +-5° for the stabilator deflection.

During a flight, the faulty elevator control surface might stuck at certain fixed angle. If this condition occurs, the stabilator needs to overcome the force created by the elevator to maintain the pitch stability. Thus, another test was conducted in the wind tunnel using variable elevator and horizontal stabilizer angle. For this test, the elevator is varied from 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40° and 45°. Lift, in Grams, is measured from the resultant elevator deflection. Next, at each elevator angle, the horizontal stabilizer is deflected at a negative angle until the lift generated equals 0. This provides data for the angle needed for the stabilator to counter act the elevator force.

From the elevator angle plot in Fig. 10, increasing the elevator angle results in the increase of the lift force (measured in Grams). At elevator deflection angle of 20°, the resultant lift force of the airfoil is 150 grams. For example, if the elevator stuck at 20°, the equivalent stabilator angle needed to counter act the force is -5° (this will produce -150 Gram of lift). This counter act movement by the stabilator will stabilize the UAV back to level flight instead of the UAV deviates from its altitude. To implement the control reallocation into microcontroller successfully, data fitting process of the lift is produced and its deflection angle is carried out.

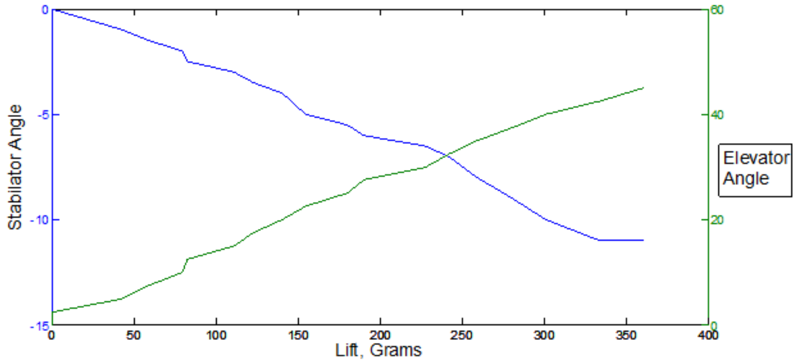


**Fig. 10. Lift generated using elevator and stabilator.**

The data fitting from Fig. 10 provide the stabilator deflection angle if the elevator stuck during flight. Eqs. (3) and (4) show the data fitting result after being processed by MATLAB.

$$\emptyset_{elevator} = -0.000063x^2 + 0.15x + 0.11 \quad (3)$$

$$\emptyset_{stabilator} = -0.0000097x^2 + 0.029x + 0.13 \quad (4)$$

For the implementation of the control reallocation, elevator position ($\emptyset_{elevator}$) is known at any given time with the installation of a position sensor. Solving for the root of Eq. (3), will result in the force generated by the elevator. The force value is substitute in equation 4 to solve for the stabilator angle ($\emptyset_{stabilator}$) needed to stabilize the altitude of the UAV.

## 5. Conclusions

In this paper, a design to provide control reallocation for elevator control surface of a small Unmanned Aerial Vehicle was simulated. The simulation result was compared with wind tunnel test. The control reallocation technique was used by transferring the faulty actuator to different control surface which having a healthy actuator. Without proper design and analysis, the transfer process would not be satisfied because the different force was generated by the two different control surfaces. Thus, the different gain of the actuator is needed. As the wind tunnel result provides real world application, the data fitting from the wind tunnel test was generated using MATLAB. The emphasis of this research was placed on the changeover process from faulty to healthy actuator. The primary contribution of this research was the data for the reallocation equation which was generated by data fitting. Finally, from the data fitting, control reallocation can then be implemented in the hardware for flight test verification in the future. The applied method will provide temporary stability for the UAV to safely during a mission thus avoiding severe damage.

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